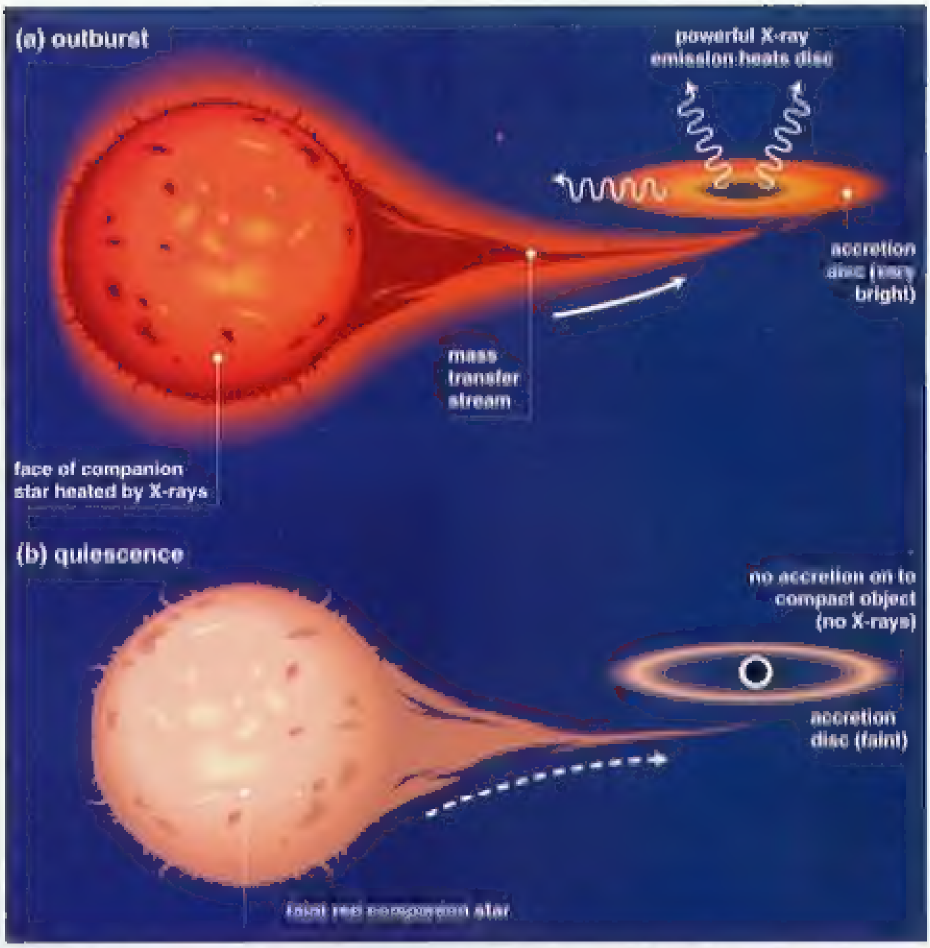
mass stars of less than 1.4 solar masses. Anything bigger would have a gravitational field capable of overcoming this degeneracy pressure, producing an even more extreme compact object, a neutron star. A neutron star is also supported by degeneracy pressure, but this time of neutrons, and at densities comparable to that of the atomic nucleus itself, unimaginably high to us on Earth.

Of course, neutron stars and their properties are now well known, principally through the study of radio and X-ray pulsars. When found in binary systems, their masses have now been very accurately determined to be around Chandrasekhar's limiting mass for a white dwarf, namely 1.4 suns.

But just how big can a neutron star get? This is actually one of the most important questions in modern astrophysics and particle physics, because to answer it both the physical structure of a neutron star, and the equation of state of matter at these densities has to be known. The latter, in particular, is of enormous importance for both cosmology and understanding the structure of the atom. Unfortunately, experimental particle physics cannot reach these densities. Consequently this is an area where astronomical observations can have enormous implications. There are, however, secure theoretical grounds to put this maximum at around three solar masses (which is reasonable given that none have been observed above two suns).

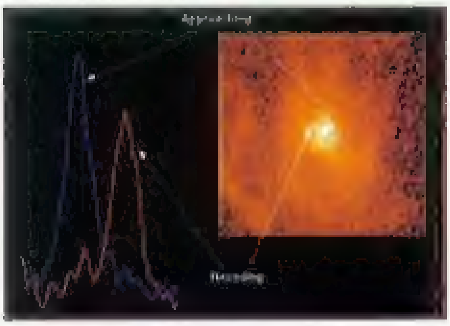
The observation of transient X-ray sources which flare up and then decay on timescales of several months has revolutionised this work by providing a significant number (now greater than 20) of extremely luminous objects which do not demonstrate any neutron star properties. More importantly, their companions are faint, low-mass stars that can effectively be used like the planets in the Solar System to infer the mass of the object they are orbiting. By observing the period and velocity amplitude of their binary motion the minimum mass of the compact object can be immediately inferred, and in the case of V404 Cyg it exceeds 6.1 suns.

One of the more accurate mass measurements of recent black hole candidate X-ray transients is that of Nova Sco 1994, but its outburst is remembered for the remarkable radio outbursts that produced, together with GRS1915+105 from the same year, the first superluminal ejections seen from a source within our galaxy.



Schematic of interacting X-ray binary in which a normal star transfers material via an accretion disc (because of the orbital angular momentum) onto its compact companion. During X-ray transient outbursts it is possible for jets of material to be ejected from near the compact object at relativistic speeds. AN graphic by Mark McLellan.

Hubble Space Telescope image and spectra of the active nucleus of galaxy M87. Image: NASA/SSci



Radio blobs are followed over a period of days by a high resolution radio interferometer (for example the VLA), and the blobs appear to move across the sky at a speed in excess of that of light. This effect is now well known in quasars and arises when the emitting region is travelling almost directly towards (or away from) the observer at a significant fraction of the speed of light. The finite light travel time then gives an illusion of the emitting blobs moving outwards at faster than light. Applying the same analysis to these new transients indicated both the direction of the jets and their actual speeds.

Measurements of the X-ray temperatures of these transients during their outbursts have yielded a very interesting result. In spite of the absorbing effects of the large amounts of interstellar gas and dust between us and these objects (they are all several thousand lightyears or more away), the two with the strongest low-temperature component are these same two superluminal transients (i.e. Nova Sco 1994 and GRS1915+105). The others are presumed to exhibit even lower temperatures which are then completely absorbed.

Remarkably, calculations of the effect of the spin of the black hole on the temperature of the gas immediately outside the event horizon show that this temperature is higher if the black hole is spinning rapidly. And such spin provides both the power and the rotation axis for the aligned relativistic jets. Such jets are therefore only expected to be seen in maximally spinning black holes.

Moving on to much larger black holes, while remaining in our own Galaxy, means raising that old problem of what is going on in its very centre. Do all galaxies contain huge dead (i.e. non-accreting) black holes? The problem with studying our own galactic centre is that there is so much obscur-

Black hole X-ray transients

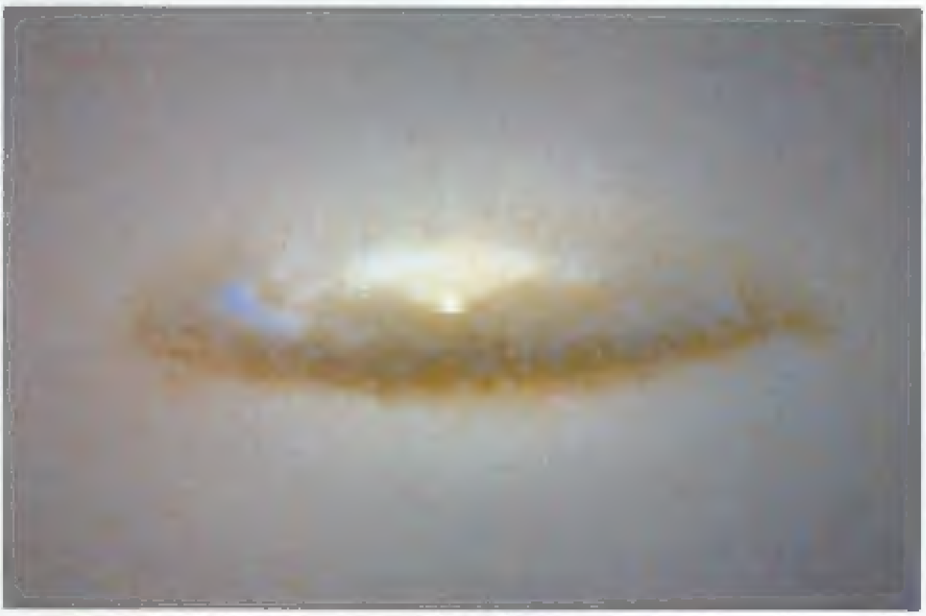
Source	Visual mag	Period (hours)	Mass (Suns)
A0620-00	18	7.7	10
V404 Cyg	18	155.3	12
N Sco 1994	17	62.6	7
G2000+25	22	8.2	10

Note how the black hole candidates seem to all be close to ten solar masses, with little evidence for a continuous distribution from neutron stars to black holes.

Black holes – do they exist?

Phil Charles **investigates whether astronomers have any observational evidence that black holes really do exist.**

It is now 30 years since John Archibald Wheeler coined the term 'black hole' to describe the ultimate in collapsed objects under Einstein's General Theory of Relativity. Since that time there have been many claims for the discovery of black holes, both in our own galaxy, and at the centre of the most distant and powerful objects in the Universe. Almost monthly, astronomers announce new observations that appear to demonstrate their existence. But are these results definitive, or could there be alternative explanations?



Resembling a gigantic hubcap in space, a 3,700 lightyear-diameter dust disc encircles a 300 million solar-mass black hole in the centre of the elliptical galaxy NGC7052. Image: NASA/SSci

Observing the neighbours

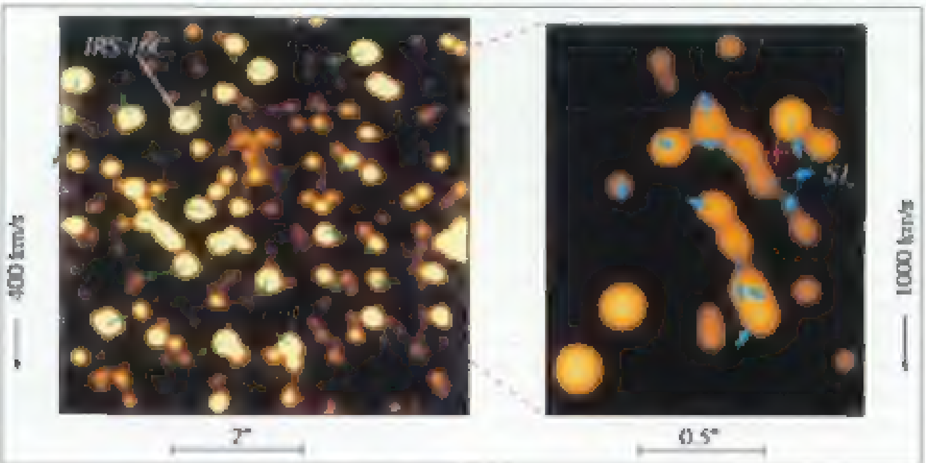
The last six years have seen major observational advances in studying what is actually going on very close to the most interesting compact objects. The problem with black holes, of course, is that, by definition, they cannot be seen.

According to relativity once an object's density becomes so high that its escape velocity equals or exceeds the speed of light, then communication in any form with that object is forever closed, since not even light can leave its surface. Consequently, all the data obtained so far on black holes is indirect. Only the effects of the putative black hole on its immediate surroundings, be they an apparently normal star in orbit around it or a giant torus of gas and dust around the very core of a galaxy, can be observed.

However, the key is in looking ever closer to that forbidden region through which light cannot pass: the event horizon. Using general relativity the effects that an ultra-dense object will have on matter that approaches the event horizon can be calculated, and then observational evidence of these effects can be searched for.

As the data becomes more detailed (using observational tools undreamt of a decade ago), and the effects are discovered, we start to acquire extremely powerful (but still circumstantial) evidence for the existence of black holes.

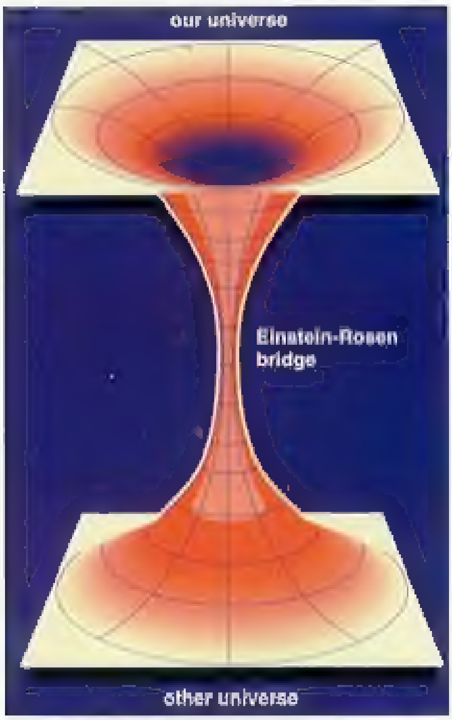
Stellar proper motions as measured in the near infrared by Eckart and Genzel from the Max Planck Institut for extraterrestrische Physik (MPE) using the MPE SHARP speckle camera at the European Southern Observatory New Technology Telescope in La Silla, Chile. The left image shows the derived proper motions as vectors (green), with length proportional to the absolute value of the motions. The right image shows the proper motion vectors (blue) in the immediate vicinity of the compact radio source SgrA* (cross). Images courtesy Andreas Eckart.

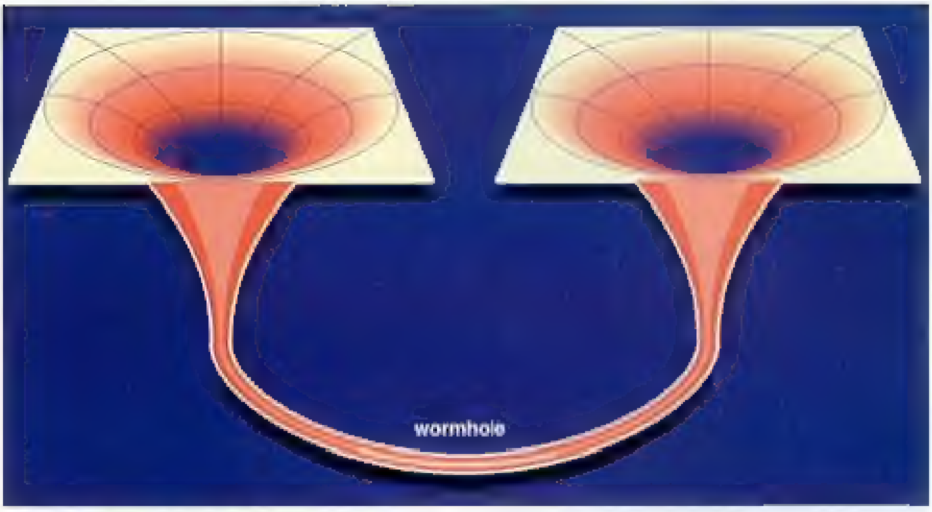


In our galaxy

It has been recognised for much of this century, that even low mass stars like the Sun end their days, when they run out of nuclear fuel, as the exotic objects known as white dwarfs. The first white dwarfs such as Sirius B were found in the 1860s. Astronomers found it astonishing that such objects could have masses comparable to the Sun (as determined from their binary orbits) and yet have the physical dimensions of the Earth! Furthermore, if all the nuclear fuel had been expended, what was stopping this extremely dense star from collapsing under its own gravity?

This question was not resolved until Chandrasekhar demonstrated that white dwarfs were held together by the degeneracy pressure of electrons. However, this solution also demonstrated that this physical force would only work for relatively low





Black holes and curved space.
ABOVE LEFT If the space-time of our universe is represented by a flat sheet, a black hole looks like a deep indentation, or 'well' in that sheet. The mathematics of General Relativity appears to suggest that this well eventually opens out into another spacetime, the link between the two being called the Einstein-Rosen bridge.
ABOVE RIGHT Some physicists have suggested that a black hole can link two regions of our own universe through a spacetime tunnel that is called a wormhole.
AN graphics by Mark McLellan.

a black hole of this kind is surrounded by an ellipsoidal region called the ergosphere within which nothing can avoid being dragged round in the direction of the black hole's rotation. In principle, it is possible to extract part of the black hole's rotational energy by sending a particle into the ergosphere.

If the particle splits in two within the ergosphere in such a way that one fragment falls into the hole, the other can emerge with more energy than the original whole particle possessed, this phenomenon being called the Penrose process after its discoverer, the British mathematician Roger Penrose.

The singularity within a rotating black hole takes the form of a ring rather than a point. In theory, it should be possible for a particle (or an observer) to fall into the event horizon, to avoid hitting the singularity and to emerge in another space-time (another 'universe', quite separate from our own) or, as some have suggested, at a different location in the space-time of our own universe.

In principle a black hole may provide a 'tunnel', known as a wormhole, that links one location in space-time with another, but the physical reality of such entities remains a matter of speculation.

Evaporating black holes

A black hole, as originally conceived, should emit nothing and should instead continue to absorb any matter or radiation that falls within its event horizon.

However, by drawing parallels between the laws governing black hole interactions and the laws of thermodynamics, and taking into account quantum phenomena, Stephen Hawking has shown that a black hole has a finite temperature and must, therefore, radiate energy and particles.

For a solar mass black hole the surface temperature would be about 10^{-7}K (one ten millionth of a degree above absolute zero). At that temperature, a black hole would radiate utterly negligible amounts of energy and would absorb far more in the form of matter and radiation from its surroundings than it would radiate.

However, the temperature of a black hole is inversely proportional to its mass. For example, if black holes with masses of the order of a billion tonnes or so (10^{12} kg) exist in the Universe today (it has been suggested that objects of this kind may have been formed in density fluctuations in the very early universe), they will have temperatures of the order of 10^{11}K and will be radiating strongly.

The lower its mass, the higher its temperature and the faster the rate at which a black hole loses mass. Therefore, if Hawking's ideas are correct, black holes lose mass at an accelerating rate and eventually evaporate in an explosive release of particles and energetic gamma rays.

Whereas a solar mass black hole would take at least 10^{66} years (about 10^{56} times the present age of the Universe) to evaporate in this way, 'mini' black holes of around 10^{12}kg ought to be evaporating now. So far, no events of this kind have been identified.

Black holes as energy sources

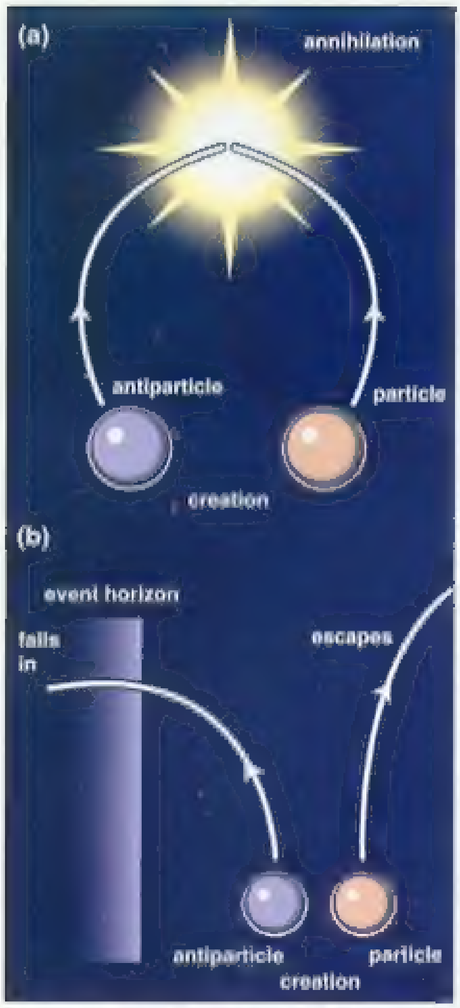
Although, apart possibly from negligible amounts of Hawking radiation, no energy can be emitted from within the event horizon, matter falling towards the event horizon is accelerated close to the speed of light and, if this matter falls into an accretion disc (a disc of matter swirling around outside the event horizon), its kinetic energy will be transformed into heat and radiant energy.

The collapse of a star to form a black hole, the subsequent 'digestion' of large clumps of matter by a black hole, or the collision and merger of two black holes, are examples of processes that release copious amounts of energy, much of it in the form of gravitational waves. Events such as these can, in principle, release energy equivalent to the complete destruction of up to 42 percent of the mass involved – a far more efficient process for liberating energy than thermonuclear fusion which, in stars, liberates less than one percent of the reacting mass in the form of energy.

Black holes in close binary systems, which are accreting mass from their companion stars, or supermassive black holes digesting gas clouds and stars at the centres of galaxies, can be among the most powerful energy sources in the Universe, and the observational evidence strongly suggests that bizarre objects such as these do indeed exist.

A black hole of a given mass could have been formed from anything at all; for example, one which formed from a collapsing star would be indistinguishable from one formed from an equivalent mass of telephone directories!

Iain Nicolson is a Visiting Fellow of the University of Hertfordshire and a contributing consultant to *Astronomy Now*.



Evaporating black holes: the Hawking process. (a) The uncertainty Principle of quantum mechanics allows pairs of particles and antiparticles to form and almost immediately annihilate each other in empty space. (b) Close to the event horizon of a black hole, very strong tidal effects may occasionally cause one member of a pair to fall in through the event horizon, leaving the other free to escape. This process converts part of the energy of the black hole's gravitational field into matter, and hence reduces the black hole's mass.
AN graphic by Mark McLellan.

the cube of its radius, the tidal force at the event horizon of a black hole decreases with the square of its mass.

For example, the tidal forces at the event horizon of a 100 solar mass black hole are a hundred times weaker than those at the event horizon of a ten solar mass black hole. Astronauts could pass through the event horizon of a ten billion solar mass black hole without experiencing discomfort (though they would soon be in dire trouble as they plunged irrevocably towards the singularity).

Time dilation and redshift

General Relativity predicts that clocks run more slowly in strong gravitational fields than in weak ones, a prediction which has been confirmed to good accuracy in a range of experiments. Gravitational time dilation becomes very large indeed in the powerful gravitational fields that exist close to the event horizons of stellar-mass black holes.

Suppose that astronauts, carrying a precisely-regulated clock, were to fall from a great distance towards the event horizon of a black hole while other observers kept watch on the infalling observers and the clock from a remote (safe) location. Initially, while the infalling astronauts were at a large distance from the event horizon, the clocks would keep in time with each other but, as the falling clock approached ever closer to the event horizon, the gravitational time dilation would become rapidly more pronounced. The distant observers would conclude that the falling clock was running ever more slowly compared to their own clocks.

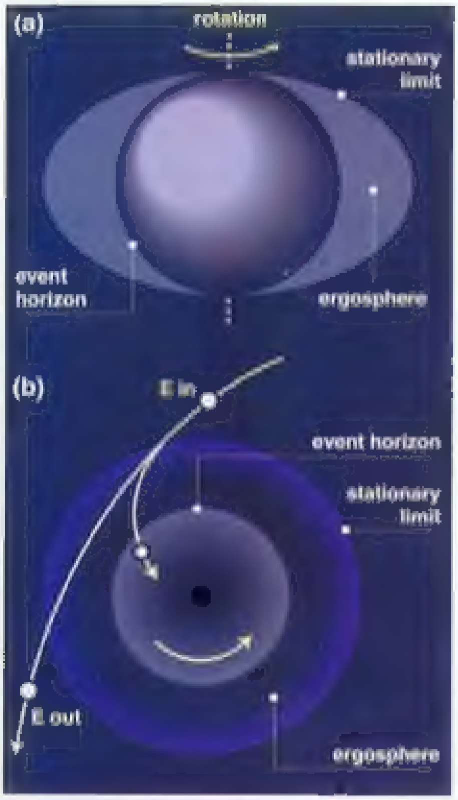
As the infalling astronauts and the clock reached the event horizon, the time interval between the penultimate and the final 'tick' of the clock would, to the distant observers, appear infinitely long. The distant observers would conclude that time had stopped for the infalling astronauts and that the astronauts, and the clock, would hover on the event horizon forever.

For the infalling astronauts and the infalling clock, time would continue to pass at its usual rate; they would plunge through the event horizon and hit the singularity about a ten thousandth of a second later. Despite the apparent conflict, each observer's view is entirely valid within their own frame of reference.

In a similar way, a collapsing star would, in principle, appear to a distant observer to hover on the event horizon into the infinite future. For that reason, before the term 'black hole' became popular, such objects were referred to as 'frozen stars'. In practice, a collapsing star will vanish when it reaches its event horizon because of the gravitational redshift, the phenomenon whereby light climbing out of a strong gravitational field loses energy, its frequency decreasing and its wavelength increasing.

Close to the event horizon, the gravitational redshift is huge, and at the event horizon it is infinitely great. As a collapsing star approached its Schwarzschild radius, all its emitted light waves would quickly become stretched out of the visible range. When it reached this radius, the distance between the penultimate and final wave crest seen by the remote observer would become infinitely great, the energy carried by the wave would become zero, and the collapsing star would vanish.

The modern theory of black holes has been developed with the aid of General Relativity – Einstein's theory of gravitation.



A rotating black hole. (a) The event horizon of a spinning black hole is surrounded by a region called the ergosphere, which is bounded by the stationary limit. Everything inside the stationary limit is dragged round by the hole's rotation. (b) The Penrose process: a particle entering the ergosphere with energy E_{in} can split in two in such a way that the escaping fragment emerges with energy (E_{out}) that is greater than E_{in}.
AN graphic by Mark McLellan.

Spinning black holes

Because nothing can escape from within the event horizon, an immense amount of information is lost when a black hole forms. A black hole of a given mass could have been formed from anything at all; for example, one which formed from a collapsing star would be indistinguishable from one formed from an equivalent mass of telephone directories! The only properties which are preserved and which can be measured by an external observer are: mass, angular momentum (a measure of the quantity of rotational motion possessed by a body) and electrical charge (although in practice it seems likely that a black hole with, for example, an initial positive charge, would quickly attract enough negatively-charged particles to cancel the charge).

Spinning black holes (sometimes called Kerr black holes after the New Zealand scientist, Roy Kerr, who first explored their properties) differ in a number of key respects from non-rotating (or Schwarzschild) ones.

The radius of the event horizon depends both on the mass and on the angular momentum of the rotating black hole, and

Sun. A dying star of this kind shrinks under its own weight until the pressure exerted by close-packed electrons (electron degeneracy pressure) is sufficiently high to prevent gravity compressing the star any further and becomes a dense white dwarf. It will be comparable in size with the Earth, and will gradually cool and fade.

When the core of a high mass star runs out of fuel, if its mass exceeds 1.4 solar masses, it will collapse almost instantaneously. During the collapse, positively-charged protons and negatively-charged electrons combine to form neutral neutrons, and the collapse will halt when the pressure exerted by close-packed neutrons becomes high enough to oppose the inward-acting force of gravity. By this time the star, or what is left of it, has become a compact neutron star, some ten kilometres in radius and with a mean density equivalent to several hundred million tonnes per cubic centimetre.

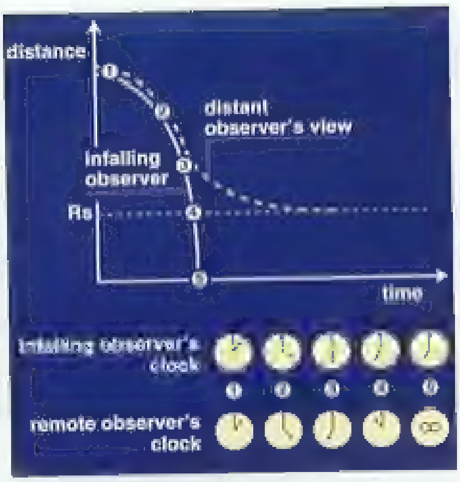
If the mass of the collapsing core exceeds the maximum permitted mass for a neutron star (between two and three solar masses), all known pressures will be overwhelmed, and it will continue to collapse until all of its mass has been compressed into a point of infinite density – a singularity.

Before this stage is reached, the collapsing star will pass inside its own Schwarzschild radius, disappear from view, and form a black hole. The outer envelope of the star may be blasted away in a supernova explosion or may instead fall into the newly formed black hole.

A black hole could also be created if a neutron star with a mass close to the maximum permitted limit were to accrete sufficient mass from a companion star to trigger its collapse.

In principle, a black hole can be formed by the gravitational collapse of any clump of matter, provided that its mass is sufficient to overwhelm all opposing forces. Black holes could, for example, have masses as great as millions or billions of solar masses, and there is good observational evidence to suggest that such objects do exist in the cores of active galaxies.

Although a star has to be compressed to an enormous density before passing inside its Schwarzschild radius (for example, a ten solar mass star would have a density of around 10^{17} kgm^{-3} – one hundred million million times the density of water – when it reached its Schwarzschild radius), supermassive black holes can be created while matter is still at quite ordinary densities.



Differing view of the fate of an infalling observer as he plunges towards a black hole. According to the infalling observer's clock, he plunges through the event horizon and hits the singularity a fraction of a second later. According to the distant observer, the infalling observer's timescale slows to a halt at the event horizon and he never reaches the singularity. AN graphic by Mark McLellan.

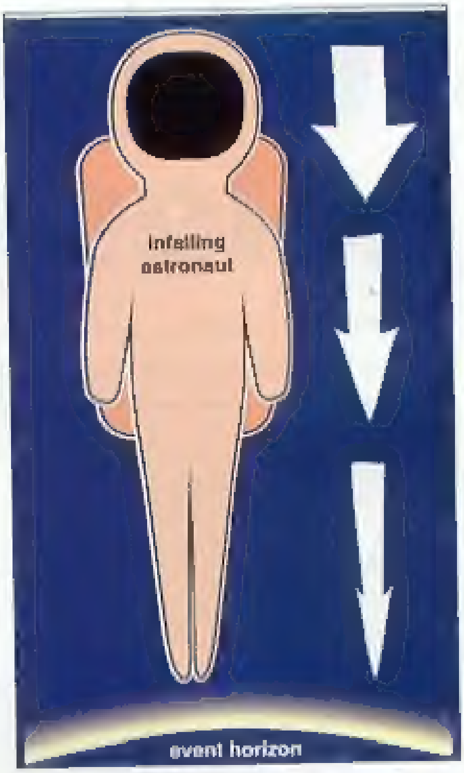
For example, a ten billion solar mass body would form a black hole if its mean density were comparable to that of air at sea level (about one kgm^{-3}).

Structure of a black hole

A simple non-rotating black hole consists of a central singularity – a point where gravity is infinitely strong and matter is infinitely compressed – surrounded by a spherical region, with a radius equal to the Schwarzschild radius. Within this radius, gravity is so powerful that nothing can move outwards. The boundary of this region is called the event horizon because no knowledge of any events which may occur inside this boundary, or 'horizon', can be communicated to the outside universe.

A photon (a 'particle' of light energy) emitted from a point inside the horizon would fall into the singularity; a photon directed radially outwards from a point just beyond the event horizon would escape, while a photon emitted at the horizon itself would, in principle, hover there forever, moving neither inwards nor outwards.

Rays of light passing close to the event horizon will be deflected by the powerful gravitational field of the black hole; the closer the approach, the greater the deflection. At a distance of 1.5 times the Schwarzschild radius, a ray will be bent into a circular path and will, unless disturbed, continue ever after to travel around the hole in a circular path. Any ray which passes inside this radius will fall into the black hole.



Tidal forces on an infalling astronaut. The arrows indicate, schematically, the strengths of the forces on the astronaut's body as he is stretched like spaghetti by the gravitational field of the black hole.
AN graphic by Mark McLellan.

Although no light or other signal can escape from within the event horizon, and a black hole cannot be seen directly, it still exerts a strong gravitational influence on its surroundings so that matter and radiation can continue to fall in, adding to the total mass of the hole and increasing its radius.

Tidal effects

When a body of finite size is located in a strong gravitational field, the difference in gravitational attraction experienced at different points on that body gives rise to a tidal force that tends to elongate the body along the direction of the field.

Anyone or anything falling towards a black hole would experience extreme tidal effects. For example, astronauts falling feet first towards the event horizon would find that their feet, being closer to the black hole, would be attracted more strongly than, and would accelerate faster than, their head. They would be stretched out on a cosmic rack of ever-increasing severity and eventually torn to shreds by escalating tidal forces. Thereafter, their shredded remains would plunge into the central singularity where they would be crushed out of existence.

However, because the radius of a black hole increases in proportion to its mass, while the tidal forces are proportional to the mass of the collapsed body divided by

An astronaut falling feet first towards the event horizon would be stretched out on a cosmic rack of ever-increasing severity and eventually torn to shreds by escalating tidal forces.

The nature of black holes explained

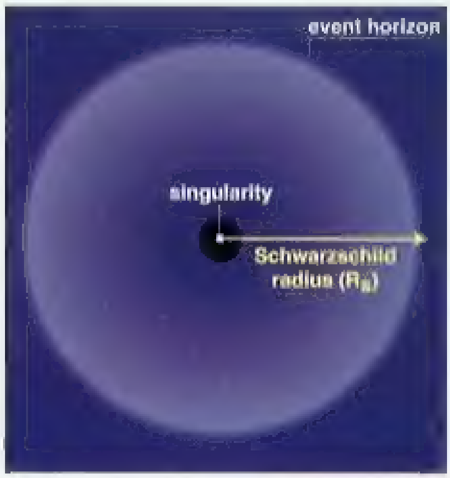
The mathematics and physics of enigmatic and mysterious black holes suggest these objects have some very strange properties. By Iain Nicolson.

A black hole is a region of space where gravity is so powerful that nothing, not even light itself, can escape from within its confines. Although Einstein's General Theory of Relativity is needed to describe the properties of black holes fully, the basic concept can be arrived at by using arguments similar to those employed in the late nineteenth century by the English natural philosopher, John Michell (in 1783), and the French mathematician, Pierre Simon de Laplace (in 1796), both of whom suggested that the most massive 'stars' in the Universe might be invisible because light could not escape from their powerful gravitational fields.

The force of gravity at the surface of a body is proportional to its mass divided by the square of its radius. Therefore, if two bodies have the same mass, but one has a smaller radius than the other, the force of gravity at the surface of the smaller body will be greater than that at the surface of the larger.

Likewise, the escape velocity (the minimum speed at which a projectile must be fired in order to continue to recede and never fall back) will be greater at the surface of the smaller body. Consequently, if a massive body is compressed, its surface gravity and escape velocity both increase, and if a body is compressed within a sufficiently small radius, its escape velocity will become equal to or greater than the speed of light.

By thinking of light as a stream of particles that would be affected by gravity in the same way that material bodies are, Laplace and Michell concluded that light would be unable to escape from bodies which were sufficiently massive, or sufficiently compressed, that their escape velocities were greater than the speed of light.

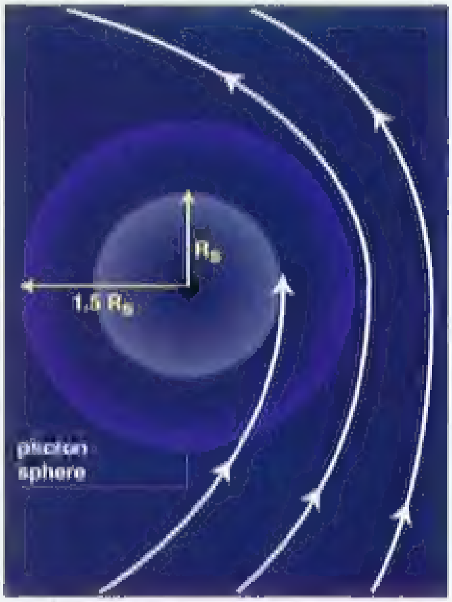


A non-rotating (Schwarzschild) black hole consists of a central singularity surrounded by an event horizon.
AN graphics by Mark McLellan.

The modern theory of black holes has been developed with the aid of General Relativity – Einstein's theory of gravitation. According to this theory, a massive body distorts, or 'curves' space (or, strictly, four-dimensional 'space-time') in its vicinity, and the paths followed by rays of light or particles of matter are determined by the curvature of the space in which they are moving.

The orbits of the planets, for example, are determined by the curvature of space in the vicinity of the Sun.

Although General Relativity treats gravity in a very different way to Newton's theory of gravitation, it leads towards a similar conclusion, namely that if a particular mass is compressed within a small enough radius, the curvature of space will be such that light will be unable to escape from within that radius. The critical radius is called the Schwarzschild radius after the German mathematician who, in 1916,



Paths followed by rays of light in the vicinity of a black hole. Photons can follow circular orbits at a distance from the singularity equal to 1.5 Schwarzschild radii.

solved Einstein's equations for the case of a compact spherical mass.

The expression for the Schwarzschild radius, R_S, is the same as that which is obtained when Newtonian theory is used to calculate the radius of a massive body with an escape velocity equal to the speed of light: $R_S = 2GM/c^2$, where G is the gravitational constant, M the mass of the body and c the speed of light.

In round figures, the value, in kilometres, of the Schwarzschild radius is 3.0M, where M is the mass of the body expressed in solar masses. The Schwarzschild radius for the Sun (M=1) is three kilometres; for a ten solar mass star, 30km; and for the Earth (with a mass equal to 1/330,000 of the Sun's mass), about nine millimetres.

General Relativity leads towards a similar conclusion, namely that if a particular mass is compressed within a small enough radius, the curvature of space will be such that light will be unable to escape from within that radius.

Formation of a black hole

While there is no natural process in the Universe today which could cause the Sun or the Earth to become a black hole, the situation is very different for high mass stars.

When stars run out of nuclear fuel, their ultimate fate is determined by their masses. The overwhelming majority of stars are comparable to, or less massive than, the